PB84-141480

Procedures for Estimating Dry Weather Sewage In-Line Pollutant Deposition. Phase 2

Environmental Design and Planning, Inc.
Boston, MA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Jan 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-141480

EPA-600/2-84-020
January 1984

PROCEDURES FOR ESTIMATING DRY WEATHER SEWAGE IN-LINE POLLUTANT DEPOSITION PHASE II

by

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Grant No. R-804578

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

TYPING GUIDE SHEET

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-84-020		PB84 141480

4. TITLE AND SUBTITLE	5. REPORT DATE
"PROCEDURES FOR ESTIMATING DRY WEATHER SEWAGE IN-LINE POLLUTANT DEPOSITION - PHASE II"	January 1984
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
William C. Pisano and Celso S. Queiroz	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Environmental Design & Planning, Inc. 19 Fordham Road Boston (Allston) Massachusetts 02134	AZB1B
	11. CONTRACT/GRANT NO.
	R-804578
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Municipal Environmental Research Laboratory-Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	Final Report-5/1/78-5/30/79
	14. SPONSORING AGENCY CODE
	EPA/600/14

15. SUPPLEMENTARY NOTES Project Officer: Richard Field, Chief, Storm and Combined Sewer Program, Edison, NJ 08837; Comm. (201) 321-6674; FTS 340-6674.

16. ABSTRACT

Planners, engineers, and municipal managers are given generalized procedures/equations to estimate the amount of pollutants deposited in combined sewer systems during dry weather so they can make intelligent decisions about sewer flushing programs and other combined sewer management controls.

The predictive equations relate the total daily mass of accumulated pollutants deposited within a collection system to the physical characteristics of collection systems such as per capita waste rate, service area, total pipe length, average pipe slope, average diameter, and other more complicated parameters that derive from analysis of pipe slope characteristics. Several other predictive equations that can be used with different available data and user resources are given. Pollutant parameters include suspended solids, volatile suspended solids, biochemical oxygen demand, chemical oxygen demand, total organic nitrogen, and total phosphorous.

The equations were developed from data assembled from three major sewerage systems in eastern Massachusetts and from a portion of the combined sewer system in the easterly district in the city of Cleveland. This study was an extension of earlier work; broader data was used here to prepare the predictive relationships.

This report was submitted in partial fulfillment of Grant No. R-804578 by Northeastern University and Environmental Design & Planning, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period of May 1, 1978 to May 30, 1979. Work was completed as of May 1979.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	34
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	

EPA Form 2220-1 (9-73)

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The deleterious effects of storm sewer discharges and combined sewer overflows upon the nation's waterways have become of increasing concern in recent times. Efforts to alleviate the problem depend in part upon the development of integrated technologies involving non-structural best management practices with structural storage and treatment concepts.

This report describes the second phase of work involving the preparation of a series of generalized predictive approaches for estimating the amount of sewage solids and other pollutants that deposit in sewerage systems during dry-weather conditions. These procedures are intended to provide estimates of overall pollutant deposition for entire sewer collection systems.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

A set of generalized procedures for estimating pollutant loadings associated with dry-weather sewage solids deposition in combined sewer systems has been prepared to provide planners, engineers and municipal managers with technical information so that they can make intelligent informed decisions on potential sewer flushing programs in combination with other combined sewer management controls.

The predictive equations relate the total daily mass of pollutant deposition accumulations within a collection system to physical characteristics of collection systems such as per capita waste rate, service area, total pipe length, average diameter and other more complicated parameters that derive from analysis of pipe slope characteristics. Several alternative predictive models are presented reflecting anticipated differences in the availability of data and user resources. Pollutant parameters include suspended solids, volatile suspended solids, biochemical oxygen demand, chemical oxygen demand, total organic nitrogen and total phosphorous.

The results presented in this study are an extension of earlier work reported by Pisano et al, (1,2). A broader data base was used in this work in preparation of the predictive relationships.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

CDF - cumulative distribution function
ft - foot (feet)
gpcd - gallons per capita per day
lb/day - pounds per day
log - logarithm
mi - mile

SYMBOLS

A - Area of collection system (acres)
BOD - Biochemical Oxygen Demand (5 day)
COD - Chemical Oxygen Demand
$\bar{D}$ - Mean pipe diameter of a collection system (inches)
e - Base of the natural logarithms
L - Total length of the collection system (ft)
L_{PD} - Length of pipe over which 80% of the total loads deposit in the collection system
PL - Percentage of pipe length corresponding to a percentage of the loads depositing in the collection system
PL_D - Percentage of pipe length corresponding to 80% of the loads depositing in the collection system
$PL_{D/4}$ - One fourth of PL_D
q - Discharge per capita, including infiltration (gpcd)
R - Multiple regression coefficient in the regression analysis
R^2 - Portion of the total variation about the mean (predicted by the regression equation) which is explained by the regression
$\bar{S}$ - Mean pipe slope of the collection system
$\bar{S}_G$ - Mean ground slope
S_{PD} - Slope corresponding to PL_D in the CDF of the pipe slopes
$S_{PD/4}$ - Slope corresponding to $PL_{D/4}$ in the CDF of the pipe slopes
S_{PL} - Slope corresponding to PL in the CDF of the pipe slopes
TKN - Total Kjeldahl Nitrogen
TP - Total Phosphorous
TS - Indicates the total mass of solids that deposit in the system (lb/day)
VSS - Volatile Suspended Solids

ACKNOWLEDGMENTS

The successful completion of this report was dependent on the cooperation and assistance of a number of individuals and organizations. We are indebted particularly to Richard Field, Chief of the Storm and Combined Sewer Section, Municipal Environmental Research Laboratory-Cincinnati, EPA, Edison, New Jersey, Richard Traver and Robert Turkeltaub, Staff Engineers of the Storm and Combined Sewer Section, for their guidance and review of the work.

This work was conducted under the supervision and direction of Dr. William C. Pisano, President, and Celso S. Queiroz, Environmental Systems Analyst, Environmental Design & Planning, Inc. (EDP). Messrs. Steven J. Rock, Martin R. Cohen and David W. Walsh, technical staff, EDP, prepared the data base for the analyses.

The Public Works Department, City of Cleveland permitted Metcalf & Eddy, Inc., Boston, Mass., to release sewerage system maps and related information to EDP.

SECTION 1

INTRODUCTION

Deposition of sewage solids during dry weather in combined sewer systems has long been recognized as a major contributor to "first-flush" phenomena occurring during wet weather runoff periods. Estimation of these loadings for a given sewer system is an extremely difficult task. Measurement for extended periods is possible but extremely expensive. Some literature information is available from experiments on build-up of sanitary sewage solids in a pilot sewer study conducted by the FMC Corporation (3). Techniques presently available to estimate dry weather deposition in sewerage systems involve the use of computerized mathematical models that are both complex and expensive, and requiring more effort than appropriate for preliminary "first-cut" assessments. (4,5)

Recently a set of generalized procedures for estimating pollutant loadings associated with dry weather sewage solids deposition in combined sewer systems was developed utilizing information from three sewerage systems in Eastern Massachusetts (1,2). A complete exposition of the analysis procedure, assumptions and methodologies has been previously given in two aforementioned documents, and will not be presented here.

The predictive equations developed in the previous study relate the total daily mass of pollutant deposition accumulations within a collection system to physical characteristics of collection systems such as per capita waste rate, service area, total pipe length, average pipe slope, average diameter and other more complicated parameters that derive from analysis of pipe slope characteristics. Several alternative predictive models were presented reflecting anticipated differences in the availability of data and user resources. Pollutant parameters include TS, VSS, BOD, COD, TKN and TP(2).Sewer system age and degree of maintenance were also considered. Factors were presented for estimating the increase in collection system deposition resulting from improper maintenance. A users guide was presented to establish the necessary data input to utilize the predictive procedures.

The objective of this study was to assess the prior predictive relationships based upon a wider data base. One recommendation from the earlier study was to add to the existing data base sewerage system information from flatter terrain with generally lower pipe slopes than previously used. Data from a flat 5314 acre parcel served by combined sewers within the City of Cleveland were prepared, assembled and added to the existing information. The empirical least squares approach was re-done. The final equations are presented along with summarized results from the earlier study.

1.1 Purpose of Study

The purpose of this study is to provide municipal managers and planners with technical information on the amount and location of pollutant deposition within sewerage collection systems so that they can make intelligent, informed decisions on the potential for sewer flushing systems in their community.

1.2 Foreword

An executive overview of the methodology used to develop the simplified deposition predictive models is presented in Section 4. Summary results of the earlier study are presented in Section 5. Details of the City of Cleveland sewerage system data base are presented in Section 6. Summary results of the analysis considering the broadened data base are given in Section 7.

1.3 Data and Information Sources

The data and information for the prior analysis were derived principally from three data sources: (a) sewer atlas physical data for portions of West Roxbury, Dedham, Newton and Brookline, Massachusetts for an infiltration/inflow study conducted by Environmental Design & Planning, Inc.(EDP) for Metropolitan District Commission (6); (b) sewer atlas physical data for portions of the City of Fitchburg, Massachusetts for a section of 208 combined sewer management study conducted by Environmental Design & Planning, Inc. for the Montachusett Regional Planning Commission (7); and (c) sewer atlas physical data for portions of Dorchester and South Boston for a combined sewer management study sponsored by the Metropolitan District Commission (8). The additional data for this study derived from a study performed by Metcalf & Eddy, Inc., Boston, Massachusetts, for the City of Cleveland Public Works Department (9).

SECTION 2

CONCLUSIONS

Conclusions derived from this investigation are as follows:

1. This present study refines an existing methodology for providing first-cut assessments of the total amounts of solids and other pollution indicators (lb/day) that deposit in a sewerage collection system. In an earlier study, a complex distributed-parameter dry weather sewage deposition model was first applied to 75 separate and combined sewer collection systems in Eastern Massachusetts to generate estimates of solids deposited in the systems (lb/day)(1, 2). These estimated loads from 75 collection systems were then regressed with selected variables representing the physical characteristics of the collection system resulting in four predictive single term power functions with at most four independent variables. The regression analysis revealed a remarkable degree of fit of the non-linear functions to the data set, with the R^2 values ranging from 0.85 to 0.95. In this study, similar data were prepared for 28 combined sewer collection systems in the City of Cleveland and appended to the data set prepared for the Eastern Massachusetts sewerage systems. The earlier regression analyses were repeated yielding similar non-linear relationships as before with high degrees of fit (R^2 ranging from 0.88 to 0.94).

2. A rudimentary sensitivity analysis was performed testing the predictive capability of both the elaborate and simple models. The analysis showed that the simpler models provided a higher degree of predictive ability. In addition, the simpler models require comparatively less effort to prepare the necessary input data and are therefore recommended in preference to the elaborate models.

3. Coefficients of the simpler model developed from the combined data base in this study are numerically very similar to those presented for the same model form in the prior study. The updated version of the simpler collection system deposition model is therefore preferred since it was based on a broader data base.

4. Extensive statistical analyses of sewerage systems pipe slope data performed in the prior study (1,2) revealed that collection system pipe slopes can be represented by an exponential probability model. Analyses of the City of Cleveland pipe slope data revealed similar characteristics. These findings provide further support for an approach described in the earlier effort (1,2) for estimating the total fraction of collection system pipe footage over which a given percentage of total loads deposit.

SECTION 3

RECOMMENDATIONS

1. The deposition prediction methodology presented in this report and in earlier work (1,2) is derived from a least squares reduction of an enormous amount of data produced from various complex computer model manipulations with the aim of producing simplified procedures to bypass the necessity of using complicated models. The complicated prediction models presented in the earlier study were roughly calibrated using field data from flushing experiments conducted over a two year period on four streets in Dorchester, Massachusetts (2). Since the addition of the City of Cleveland data to the original data base and the accompanying regression analysis support the original findings, actual field data relating to deposition characteristics within segments of the Cleveland systems analyzed should be collected. This data would add further credibility to the overall approach.

2. Both the complicated and simplified predictive procedures for estimating daily dry weather sewage deposition loadings within collection systems should be further verified using field information collected from other sewerage collection systems not used in model development data base.

3. The predictive equations should be incorporated into the U.S. EPA Storm Water Management Model for estimating pollutant deposition loadings in sewerage collection systems where individual pipe segments of small diameter are not normally modeled.

4. Another area meriting further study is the analysis of the cumulative distribution function of pipe slopes, especially for applications where only a limited amount of information on the collection system is available.

SECTION 4

METHODOLOGY

4.1 Overview of Approach

An empirical model relating pollutant deposition loadings to collection system characteristics is the goal of this study. The approach is to use least squares to fit parameters of a postulated model. The model form is a single-term power function relating total daily sewage solids deposition over a collection system to simple sewershed characteristics, including, for example, service area, length of pipe and average pipe slope. The major steps in the analysis are depicted in Figure 1. Sewer system data including manhole-to-manhole length, slope, size, shape and age are assembled for entire collection systems in Step A. This information is used in Step B to compare total daily sewage solids deposited in these collection systems for a wide variety of different operating conditions. These quantities are estimated using an existing exogenous model that uses extremely detailed information to compute deposition loadings throughout an entire collection system network.

The simulated deposition loadings for different input conditions constitute the dependent variable data in the regression analysis. The independent variable data is prepared in Step C as a result of the analysis of assembled data from Step A and detailed outputs from Step B. The dependent variable data was generated from an exogenous predictive analysis, while the independent variable data was obtained from primary collection system data and from a secondary analysis of the exogenous simulation outputs with selected collection system data.

The regression analysis is performed in Step D to prepare the simplified predictive relationships. The entire process is designed to eliminate using the complicated network model requiring thousands of individual bits of technical information.

4.2 Variables Considered

The list of variables considered in the regression analysis is the following:

1. Total collection system pipe length (L) - ft;
2. Service area of collection system (A) - acres;
3. Average collection system pipe slope ($\bar{S}$) - ft/ft;

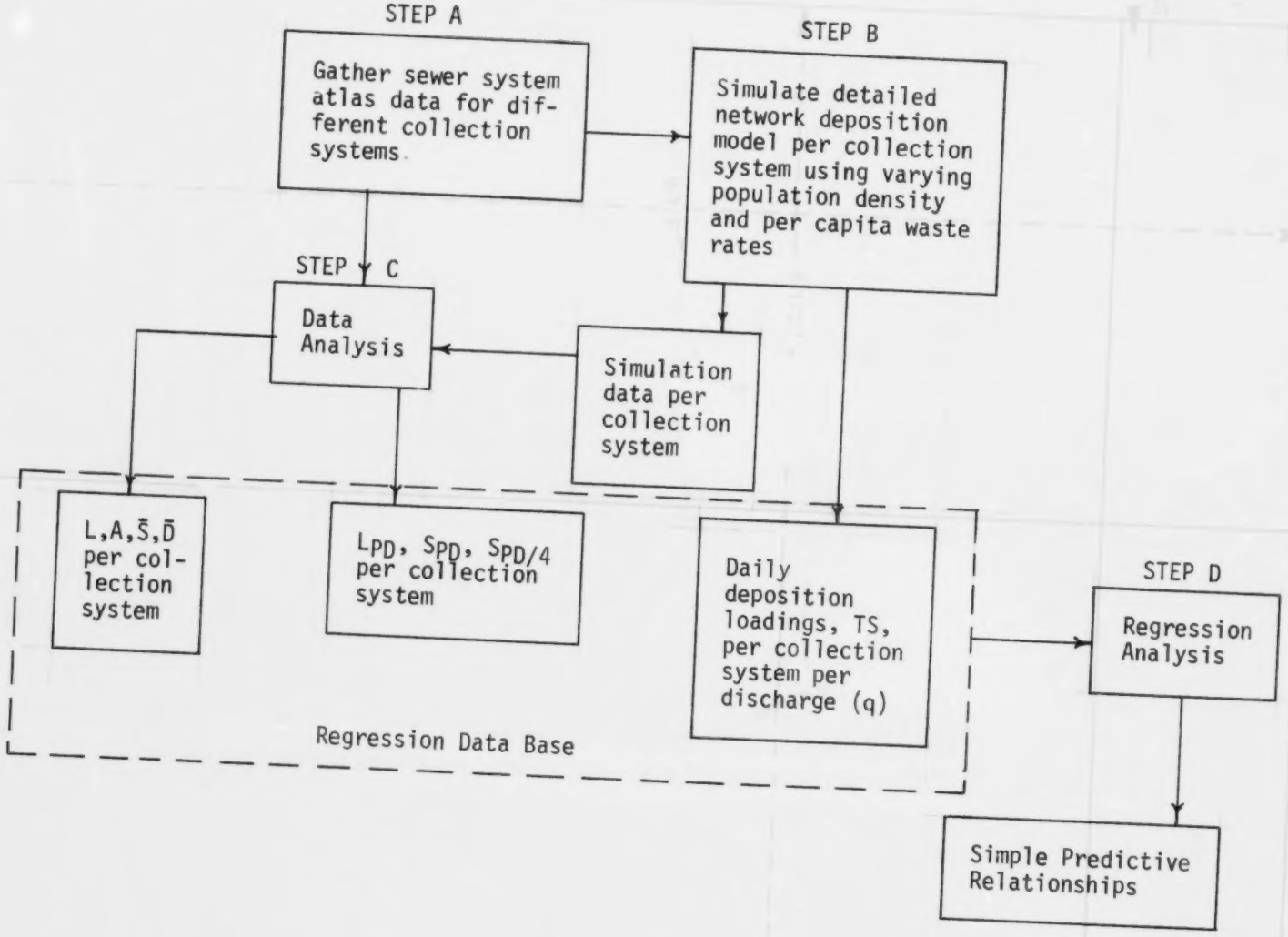
STEP A
Gather sewer system atlas data for different collection systems.
STEP B
Simulate detailed network deposition model per collection system using varying population density and per capita waste rates
STEP C
Data Analysis
Simulation data per collection system
L,A,S̄,D̄ per collection system
LPD, SPD, SPD/4 per collection system
Daily deposition loadings, TS, per collection system per discharge (q)
Regression Data Base
STEP D
Regression Analysis
Simple Predictive Relationships

FIGURE 1: OVERVIEW OF APPROACH

4. Average collection system pipe diameter ($\bar{D}$) - inches;

5. Length of pipe corresponding to 80% of the solids deposited in the system (L_{PD}) - ft;

6. Slope corresponding to L_{PD} (S_{PD}) - ft/ft;

7. Slope corresponding to 1/4 of the percentage of pipe length (PL_D) below which 80% of the solids deposit ($S_{PD/4}$) -- ft/ft;

8. Flow rate per capita, including allowance for infiltration (q) - gpcd; and

9. Daily total sewage solids deposition loading in collection system (TS) - lb/day. (predicted from deposition model)

It was determined in the prior study that the mean pipe slope alone would not be adequate to explain the effects of the pipe slopes on the variations of the deposition loads. A better characterization of the collection system pipe slopes could be obtained by defining various parameters at the flatter pipe slope range. Two other pipe slope parameters besides the mean pipe slope were selected for inclusion into the regression model.

The collection system slope parameters S_{PD} and $S_{PD/4}$ were arbitrarily defined with the sole aim of better defining the lower range of the pipe slope distribution function. These collection system slope parameters were defined after reviewing several plots of the cumulative distribution of pipe slopes for several collection systems. Other choices could have also been made.

Estimates of collection system pipe length, service area, average pipe slope and average diameter were prepared from direct inventory and analysis of sewer system atlas information. Estimates of L_{PD}, S_{PD} and $S_{PD/4}$ were prepared from a detailed analysis of simulated data generated from a complex sewer system network deposition model. The total daily deposition load, TS, is also computed using this model.

4.3 Model Forms

Both linear additive and multiplicative models were investigated. Untransformed observed values of the dependent and independent variables were initially used, leading to a strictly linear regression equation. In the second case the observed values of both the dependent and independent variables were transformed by taking their natural logarithms, leading to a linear equation in the logarithmic domain which can be put into a non-linear multiplicative form.

4.4 Regression Method

The linear regression program used to empirically establish the relationships of the total daily suspended solids (TS) deposition within a sewerage collection system with the independent variables is one that operates in a step-forward manner. At each step in the analysis, the particular variable entered into the regression equation accounts for the greatest amount of variance between it and the dependent variable, i.e., the variable with the highest partial correlation with the dependent variable. The program is flexible to allow any independent variable to be: (1) left free to enter the regression equation by a criterion of the sum of squares reduction; (2) forced into the regression equation; or (3) kept definitely out of the regression equation in one given selection. The procedure permits examination of several alternative considerations of the independent variables by optional selections of variables to be forced in and out of the regression equation, or to be simply left free to enter the equation using variance reduction criteria.

Observation of the relative change in the standard error of estimate was used as the stopping rule in the regression analysis. An increase of the standard error at a given step indicates that the additional information realized by introducing the variable is off-set by the loss in degrees of freedom, implying that the regression equation is better off without that particular variable.

The Student's t statistics computed for each of the regression coefficients of the final relationships all exceeded 4.0, and averaged about 9.5 using the aforementioned stopping rule. A value of 1.96 is considered statistically significant at 95 percent confidence limits for large sample size (greater than 100 observations).

SECTION 5

SUMMARY OF PRIOR RESULTS

5.1 Introduction

Regression results reported in earlier work (1,2) are summarized in this section. Various predictive models are described, relating total suspended solids deposition within a collection system with independent variables under the assumption of clean pipe conditions. These relationships are therefore applicable for situations in which the sewer piping system is properly maintained. These equations were developed from data assembled from three major sewerage systems in Eastern Massachusetts.

The physical characteristics of the three major collection systems used in this analysis derived from three prior studies. The first area, covering portions of West Roxbury in Boston, Dedham, Newton and Brookline is strictly separated. The second area covering major portions of Dorchester and South Boston, two neighborhoods of the Boston metropolitan area, is a mixed, combined and separate area, while the third basin covering a portion of the City of Fitchburg is served by a combined sewer system. The total pipe footage for all three areas entails 196 miles of separate and combined sewer systems encompassing a total area of 8.9 square miles.

Alternative relationships for estimating total daily solids deposition are presented in section 5.2. Empirical equations are presented in section 5.3 for obtaining estimates of pipe length and average slope from readily available data.

5.2 Alternative Model Selections

In this section several regression models are recommended for user application. Alternative forms reflecting the availability of data and/or user resources will be presented. The simplest forms require little data and have the least predictive reliability, whereas the more complicated models, requiring greater user resources and data availability, provide estimates with extremely high reliability.

The Elaborate Model. The highest multiple correlation coefficient, 0.974 (R^2 = 0.949) was obtained using the model given by equation 1.

$$TS = 0.0038\ L^{0.814}\ S_{PD}^{-0.819}\ S_{PD/4}^{-0.108}\ q^{-0.510}\ (R^2=0.949), \qquad (1)$$

where TS is deposited solids loading in lbs/day, L is total length of sewer system in feet, Sp_D and $Sp_{D/4}$ are the slope parameters defined in section 4.2, and q is the per capita waste rate in gpcd.

Utilization of equation 1 requires knowledge of total pipe length, the per capita contribution and the two pipe slope parameters, Sp_D and $Sp_{D/4}$. These slope parameters in turn are a function of the percentage of pipe, where 80% of the total mass (TS) deposits (PL_D) and the probability distribution of the pipe slopes. The value PL_D is derived from the extensive computer analyses. A discussion involving estimation of this parameter is reported elsewhere.(1,2). The probability distribution of the pipe slopes can either be derived from histograms computed from local pipe slope data, or it can be defined with reasonable approximation from the mean pipe slope ($\bar{S}$) only (1,2). If the pipe slopes are not available, a regression relationship of mean ground slope, SG, and mean pipe slopes, can be used to estimate mean pipe slope.

An Intermediate Model. A simpler model than that given by equation 1, including only the primary variables, is given by:

$$TS = 0.00130\ L^{1.180} A^{-0.178} (\bar{S})^{-0.418} (\bar{D})^{0.604} q^{-0.510} (R^2 = 0.852), \quad (2)$$

where $\bar{S}$ is average pipe slope; $\bar{D}$ is the average equivalent diameter in inches; and A is service area (acres).

All five independent variables present in equation 2 can be defined with good precision in any practical application. Neither the distribution of deposited loads versus pipe length, nor the probability distribution of the pipe slopes, are required. The mean pipe slope, $\bar{S}$, again can be correlated to the mean ground slope if no information on pipe slopes is available. A fitted equation for L as a function of A was derived from the data used in this study, and is presented in section 5.3.

If the mean pipe diameter, $\bar{D}$, is eliminated from this regression, the loss in precision of the estimates is not significant, resulting in the expression:

$$TS = 0.00389\ L^{1.220} A^{-0.187} (\bar{S})^{-0.434} q^{-0.510} (R^2 = 0.848). \quad (3)$$

The Simplest Model. The highest R^2 value that can be obtained with the least number of independent variables is given by the regression equation:

$$TS = 0.0076\ L^{1.063} (\bar{S})^{-0.436} q^{-0.510} (R^2 = 0.845). \quad (4)$$

5.3 Estimation of Total Pipe Length

The total pipe length of the system, L, and its corresponding collection area, A, are generally assumed to be known. In cases where this

information is not known and where crude estimates will suffice, the total pipe length can be estimated from the total basin area using the expressions:

$$L = 168.95\ A^{0.928}\ (R^2=0.821)\ \text{- low population density (10-20 people/acre)}$$

$$L = 239.41\ A^{0.928}\ (R^2=0.821)\ \text{- moderate-high population density (30-60 people/acre)} \qquad (5)$$

5.4 Estimation of Pipe Slope

If data on pipe slope is not available, an approximate estimate can be obtained by computing a mean value for the ground slope using any procedure, such as the techniques of uniform grid sampling or random sampling. With the mean ground slope value, determine the mean pipe slope by:

$$\bar{S} = 0.348\ (\bar{S}_G)^{0.818}\ (R^2=0.96), \qquad (6)$$

where $\bar{S}_G$ = mean ground slope (ft/ft).

The expression above resulted from a regression of mean ground versus mean pipe slope for all 75 basins of this study. The resulting correlation coefficient was 0.98.

This relation was derived in the following manner. Topographic mylar overlays with ground contour at ten feet intervals were developed for the three sewerage system service areas in Eastern Massachusetts. Using the topographic maps, the collection system areas were subdivided into smaller fractions considered to have uniform slopes. The ground slopes were computed for each of the subareas. Those ground slopes were then associated with the percentages of the collection system area they covered. The basin average ground slope was then computed by weighing the individual slopes by their associate subarea percentages.

SECTION 6

CLEVELAND SEWERAGE SYSTEM DATA

6.1 Introduction

Metcalf & Eddy, Inc. (M&E) prepared a study in 1973 for the City of Cleveland, investigating improvements needed to mitigate flooding problems via computer modeling of the sewer system in the Easterly District, and to identify orders of priority for necessary improvements along with associated costs (8).

First of all, the flooding conditions and transport capabilities in the existing system were determined by computer simulation. Then, based on these results, the necessary sewer sizes were estimated to eliminate flooding under the design storm conditions. Computer simulation was then used to test the adequacy of the selected improvements.

M&E modeled all sewers 30 inches in diameter (or equivalent in size) and larger, and, in certain areas where the nature of the tributary area was complex, smaller pipes were also included. Pipes smaller than 30 inches in diameter were analyzed on a tributary area basis. Selected typical areas were modeled in order to generate tables for flow quantification which could be used to determine the required size of sewers in the area on the basis of tributary area characteristics such as size, slope, and percent imperviousness.

After clearance with the City of Cleveland, EDP acquired schematic sewer system maps of selected catchment areas and data sheets showing physical dimensions of the sewer system components from M & E.

6.2 General Description

The Easterly District in the City of Cleveland is bordered on the west by the Westerly District extending along the Cuyahoga River; on the south by the Southerly District, generally extending along Woodland, Holton, Parkhill and Abell avenues; on the east by the communities of Euclid, Cleveland Heights, South Euclid, East Cleveland, and Shaker Heights; and on the north by Lake Erie. The Easterly District of the City totals approximately 16,000 acres and includes the downtown area, with an additional 25,000 acres tributary from the surrounding areas.

The existing sewerage system within the Easterly District is almost entirely combined. Tributary areas outside of the City use City sewers and drains for conveyance of drainage to downstream water courses. The available topographic data showed that most of the Easterly District is relatively flat with a ground slope under 2.0 percent averaging at about 0.5 percent.

6.3 Data Preparation

M&E had divided the Eastern District into 24 major catchment areas. After review of the system map, EDP selected three areas for detailed areas. These systems are referenced as areas 9, 10 and 11. The total service area of the system modeled by EDP is 5314 acres, entailing roughly 476,700 feet of combined sewers. Pipe sizes ranged from 12" to 120". Approximately 20% of all pipes were non-circular in shape. EDP subdivided the three catchment areas into 28 sections and represented the entire system by a network link-node configuration totaling 1590 segments.

The data furnished by M&E were incomplete in some instances, thereby requiring estimation of pipe diameter and slope for a number of the laterals feeding into feeders and trunk sewers. The data were then checked, tabulated and data processed. Summary statistics of the Cleveland sewerage system characteristics considered in the analysis are presented in Table 1.

TABLE 1

SUMMARY OF SEWERAGE SYSTEM STATISTICS

Parameter	Mean*	Standard Deviation
L (feet)	17025	8240
A (acres)	189.8	87.8
$\bar{D}$ (inches)**	28.5	31.1
$\bar{S}$ (ft/ft)	.0048	.0027

* Number of service subareas (sections)=28
** Equivalent circular diameter

6.4 Distribution of Pipe Slopes

The regression model included several collection system pipe slope parameters, S_{PD} and $S_{PD/4}$, that required computation of the cumulative pipe slope distributions. A computer program was used to compute these distributions from data on the pipe segments upstream and downstream invert elevations and segment lengths. The program computed the slope distribution weighing the segment slopes by their lengths. The mean standard deviation, coefficient of variation, coefficient of skewness and coefficient of kurtosis of pipe slopes per collection system were also computed. The program computed the distribution and the aforementioned statistics for each system.

Plots of the cumulative slope distributions for a few basins indicated concave shapes without a point of inflexion. Plots of the complementary

CDF of the pipe slopes on semi-logarithmic paper resulted in remarkably linear shapes. Although no formal numerical test of goodness-of-fit was performed, this fact indicates that, at least for the sample data used, the distribution of the pipe slopes is exponential. Pipe slope data analyzed in the earlier investigation of sewerage system information from Eastern Massachusetts were also found to be exponentially distributed.

Pipe slope cumulative distributions and the corresponding cumulative distributions of solids deposited versus pipe lengths computed for each collection system were used to estimate the special slope parameters, Sp_D and $Sp_D/4$. The distribution of solids deposited per collection system were prepared using the simulated results of the detailed deposition model described in sections 6.5 and 6.6.

6.5 Deposition Model

The deposition model used in this study to generate estimates of solids deposition in the 28 collection systems is described in detail elsewhere (1). The model considers peak daily dry weather flow and uses a shear stress criterion to determine the limiting diameter of the solids particles that deposit at each segment. Then, with this limiting particle size, and assuming a given distribution for the particle sizes present in the dry weather sanitary flow, the model determines the percentage of the suspended solids that deposit at each pipe segment. The model also has mechanisms to account for the fact that particles of diameters up to a given size that deposit in a given pipe segment are not available for deposition in downstream segments.

Some of the results given by the model are: (1) the flow conditions at each pipe segment, including discharge, average velocity, water depth and shear stress; (2) the loads (lb/day) deposited at each pipe segment; and (3) the accumulated value of the loads deposited in all upstream segments.

6.6 Detailed Deposition Model Analysis

The detailed network deposition model was then run for each of the 28 systems under varying per capita dry weather waste rates. The dry weather discharge in a sewer system is dependent upon the local population density, the domestic per capita contribution, the degree of infiltration and any industrial waste contributions.

It was envisioned that a single per capital surrogate waste rate would be generated incorporating a wide range of population density and infiltration conditions encountered in practice. This variable would embed all these variations and be used in both the deposition model to predict daily dry weather solids deposition and in the regression model as an independent variable.

Population densities ranging from 15 people/acre up to 90 people/acre were considered. Using a factor of 0.035 miles of sewer per acre, the corresponding number of people per 100 feet of sewer pipe was computed. These factors are used in the deposition model which requires as input the number of people per 100 feet of sewer.

The dry weather per capita contribution of 85 gpcd was considered fixed in this analysis. Four different infiltration estimates of 500, 1000, 2000 and 4000 gallons per acre per day were used to cover the range of normally encountered infiltration conditions. The per capita waste rates were adjusted to incorporate the various rates of infiltration for the range of population densities considered in the analysis. These per capita values were again adjusted to the mid-range of population density of 45 people/acre. This last conversion permits considering one single range of surrogate per capita flow rates using 45 people/acre as the norm. Four different flow rates are considered in the analysis and cover the full range of per capita waste rates for different population densities and infiltration conditions. The per capita waste rates used in the analysis are: 40 gpcd, 110 gpcd, 190 gpcd and 260 gpcd.

The per capita solids waste rate of 0.5 lb/capita/day was used in all computations. This parameter was established from field measurements in the sewer flushing project (2). All regression results presented in Sections 5 and 6 can be linearly scaled for any other desired per capita solids waste rate.

6.7 Distribution of Solids Deposited by Pipe Length

The cumulative distribution of solids deposited in the collection system versus the cumulative length of sewer pipe where the deposition occurs is the only exogenous information that the user will have to accept in applying this methodology. In other words, this distribution is the only information that cannot be derived from local data and can only be modified in a minor way by input from local conditions.

Plots of several cumulative probability functions for a few collection systems are presented in Figure 2. Plots in semi-log paper on the complementary values of the load probabilities (in the log axis) versus the cumulative probability of pipe lengths, resulted in nearly straight lines, indicating that this distribution is also exponential.

Figure 3 shows the relationship between cumulative pipe slope and solids deposition functions in deriving the pipe slope parameters, S_{PD} and $S_{PD/4}$. The selection of the 80 percentile solids deposition level for determination of the two slope parameters is discussed in earlier work (1,2).

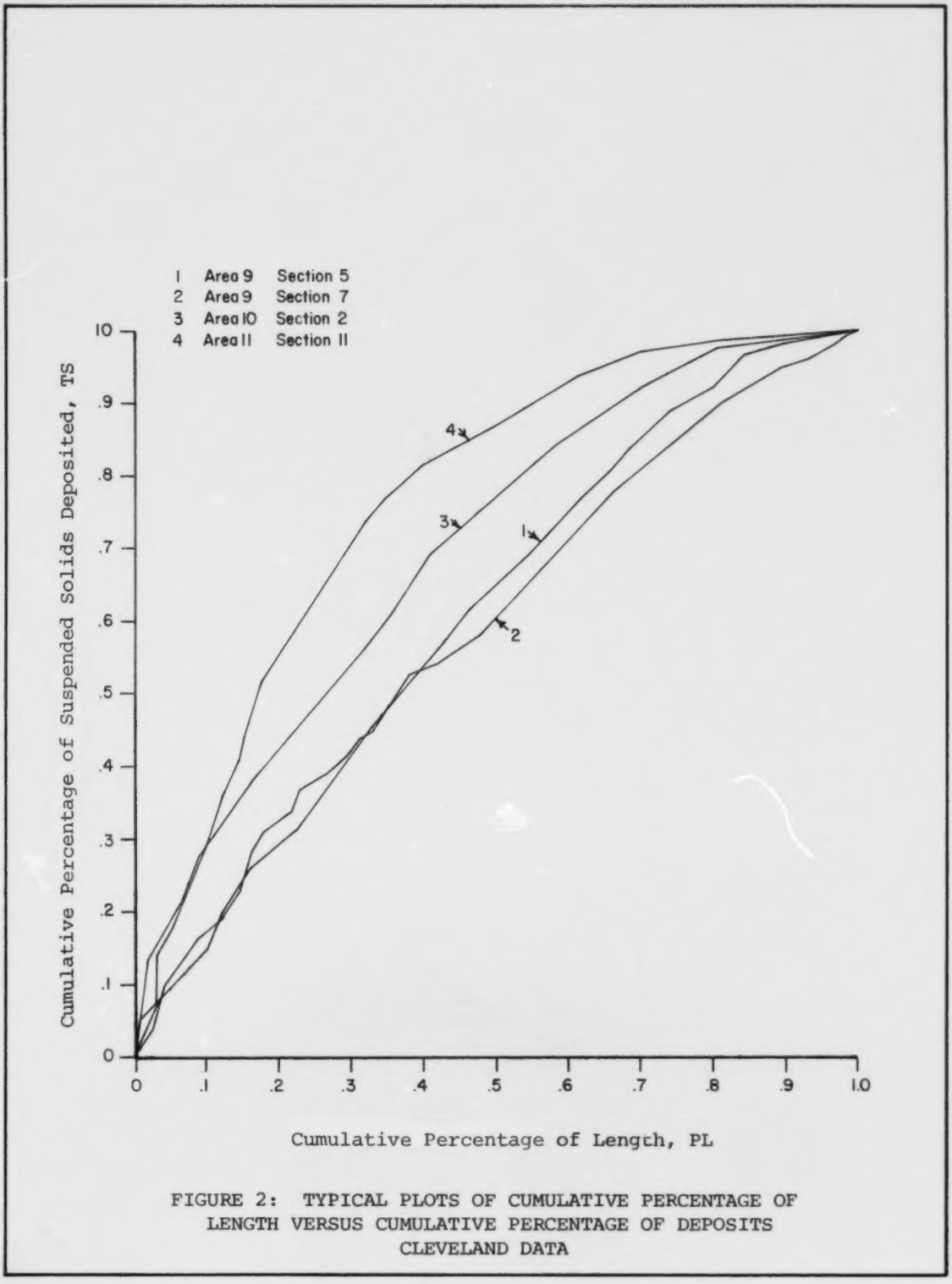

FIGURE 2: TYPICAL PLOTS OF CUMULATIVE PERCENTAGE OF LENGTH VERSUS CUMULATIVE PERCENTAGE OF DEPOSITS CLEVELAND DATA

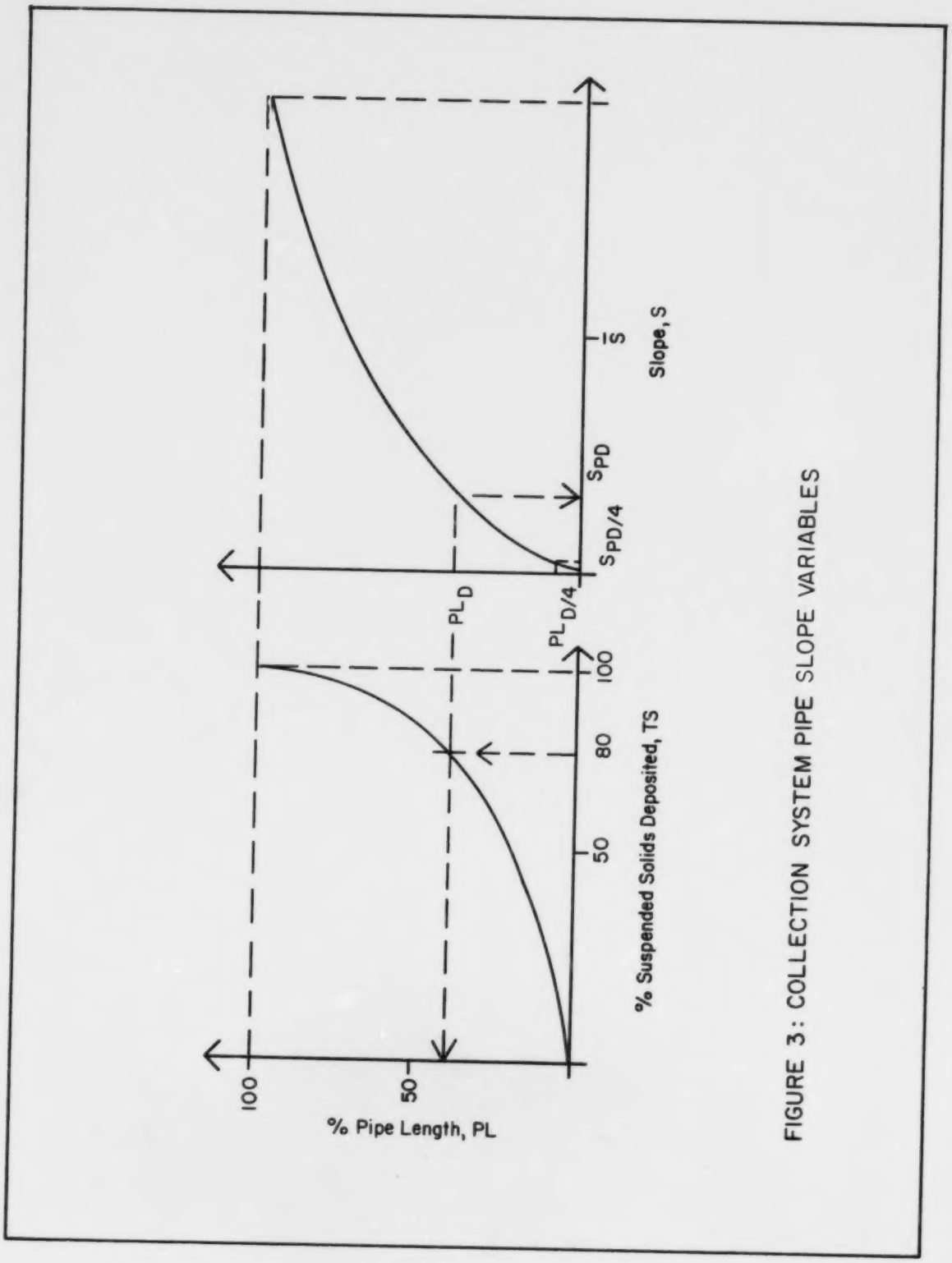

FIGURE 3: COLLECTION SYSTEM PIPE SLOPE VARIABLES

SECTION 7

SUMMARY OF NEW RESULTS

7.1 Introduction

Regression results using the augmented data base are summarized in this section. Various predictive models are described, relating total suspended solids deposition within a collection system with independent variables under the assumption of clean pipe conditions. These relationships are therefore applicable for situations in which the sewer piping system is properly maintained. These equations were developed from data assembled from three major sewerage systems in Eastern Massachusetts and from a portion of the combined sewer system in the Easterly District in the City of Cleveland.

Statistical summary of the data used in the regression analysis is given in section 7.2. Alternative relationships for estimating total daily solids deposition are presented in section 7.3. Empirical equations are presented in section 7.4 and 7.5 for obtaining estimates of pipe length and average slope. A discussion of results is presented in section 7.6.

7.2 Statistical Summary of Regression Data

The means and standard deviations of the independent variables used in this regression analysis for both the prior and augmented data base are given in Table 2. Sewer shed characteristics for seventy-five collection systems from the three major sewerage systems in Eastern Massachusetts comprise the prior data base. Characteristics from 28 collection systems located within the Easterly District of the City of Cleveland combined sewer system were used to augment the Eastern Massachusetts data. Average pipe length per sewer shed, L, size of service area, A, and average collection system pipe diameter, D, of the augmented data base increased over prior results. The average slope parameters, $\bar{S}$, S_{PD} and $S_{PD/4}$ all decreased by including collection system data from the relatively flat Cleveland collection systems.

The average daily collection system deposition loadings for all 113 areas computed over all four per capita waste discharge levels is 1.94 lb/day per acre of service area. The mean and standard deviation of the loadings computed for a per capita waste rate of 260 gpcd are 1.07 and 1.64 lb/day per acre of service area, respectively. The average deposition rates per acre of service area for per capita waste rates of 190, 110 and 40 gpcd are 1.35, 1.91 and 3.42 lb/day.

TABLE 2: MEANS AND STANDARD DEVIATIONS OF THE INDEPENDENT VARIABLES USED IN THE REGRESSION

Variable	A		B	
	Mean	Standard Deviation	Mean	Standard Deviation
L (ft)	13702	22867.	14720.	20044.
A (acre)	76.	102.	106.9	110.8
$\bar{S}$ (ft/ft)	0.0210	0.0126	0.0166	0.0130
$\bar{D}$ (in)	11.5	2.0	16.9	6.1
S_{PD} (ft/ft)	0.0101	0.0093	0.0067	0.0072
$S_{PD/4}$ (ft/ft)	0.0037	0.0033	0.0034	0.0029

A - Eastern Massachusetts Data - 75 collection systems
B - All Data (Eastern Massachusetts + Cleveland) - 103 collection systems

7.3 Alternative Model Selections

In this section several regression models are recommended for user application. Alternative forms reflecting the availability of data and/or user resources will be presented. The simplest form requires little data and has the least predictive reliability, whereas the more complicated model, requiring greater user resources and data availability, provides estimates with extremely high reliability.

The Elaborate Model. The highest multiple correlation coefficient, 0.969 ($R^2 = 0.940$) was obtained using the model given by equation 7:

$$TS = 0.00108\, L^{0.948}\, \bar{S}^{-0.323}\, S_{PD}^{-0.519}\, S_{PD/4}^{-0.148}\, q^{-0.518} \quad (R^2=0.940) \qquad (7)$$

where TS is deposited solids loading in lb /day, L is total length of sewer system in feet, $\bar{S}$ is the average collection system pipe slope, S_{PD} and $S_{PD/4}$ are the slope parameters defined in section 4.2, and q is the per capita waste rate in gpcd.

Utilization of equation 7 requires knowledge of total pipe length, the per capita contribution and the three pipe slope parameters, $\bar{S}$, S_{PD} and $S_{PD/4}$. The slope parameter, S_{PD}, is a function of the percentage of pipe, where 80% of the total mass (TS) deposits (PL_D), and the probability distrib-

ution of the pipe slopes. The value PL_D is derived from the extensive computer analyses. A discussion involving estimation of S_{PD} and $S_{PD/4}$ are reported elsewhere (1,2). The probability distribution of the pipe slopes can either be derived from histograms computed from local pipe slope data, or it can be defined with reasonable approximation from the mean pipe slope ($\bar{S}$) only (1,2). If the pipe slopes are not available, a regression relationship of mean ground slope and mean pipe slope can be used to estimate mean pipe slope.

Equation (7) is similar in form to equation (1) given in section 5. The average collection system slope, $\bar{S}$, entered equation (7) but not equation (1). This result is discussed in section 7.6. Although the values of exponents on the independent variables increased in abolute magnitude, the multiplicative constant of the equation decreased. Calculation of several collection system deposition estimates using equations (1) and (7) yields similar results. Either equation can be used, and will provide comparable estimates.

The Simplest Model. The highest R^2 value that can obtained with the least number of independent variables is given by the regression equation:

$$TS = 0.0088\ L^{1.065}\ (\bar{S})^{-0.433}\ q^{-0.539}\quad (R^2 = 0.880) \qquad (8)$$

The form of equation (8) is exactly the same as equation (3) given in section 5. The exponents of the independent variables and the multiplicative constant of the equation only slightly changed in comparison to the equation derived from Eastern Massachusetts collection system data. The degree of fit is high (R^2=0.880)and superior to the prior fit (R^2=0.845).

7.4 Estimation of Total Pipe Length

The total pipe length of the system, L, and its corresponding collection area, A, are generally assumed to be known. In cases where this information is not known and where crude estimates will suffice, the total pipe length can be estimated from the total basin area, using the expressions:

$$L = 220.9\ A^{0.847}\ (R^2=0.804)$$ - low population density (10-20 people/acre)

$$L = 238.0\ A^{0.847}\ (R^2=0.804)$$ - moderate-high population density (30-60 people/acre) (9)

These equations were developed from a least squares analysis of the augmented data base.

7.5 Estimation of Pipe Slope

If data on pipe slope is not available, an approximate estimate of average collection system pipe slope can be obtained by computing a mean value for the ground slope and then using equation (10) as follows:

$$\bar{S} = 0.320\ (\bar{S}_G)^{0.790}\ (R^2=0.850), \qquad (10)$$

where $\bar{S}_G$ = mean ground slope (ft/ft).

The expression above resulted from a regression of mean ground versus mean pipe slope for all 103 collection systems. The procedure used in estimating ground slope data for the Cleveland collection systems was similar to the method used in the earlier study of Eastern Massachusetts collection systems, and is included in section 5.4.

7.6 Discussion of Prior and New Results

Table 3 presents an overview of the predictive equations prepared from the original data set (75 collection systems in Eastern Massachusetts) and the new combined data set entailing information for 28 collection systems in Cleveland appended to the original data. The percentage of variance explained, R^2, for the two elaborate models (equations 1 and 7) are very similar. All three collection system slope parameters, $\bar{S}$, S_{PD} and $S_{PD/4}$, entered the regression equation at a high significance level (Student's t-values exceeding 4.0) for the combined data set, whereas, only S_{PD} and $S_{PD/4}$ entered the elaborate model for the original set. The explanation for this difference is due, in part, to the limited range of average collection system pipe slopes, $\bar{S}$, for the three sewerage systems comprising the original data set. The ranges of the average pipe slopes computed for the collection systems within each of the three sewerage systems in Eastern Massachusetts and for the 28 systems in Cleveland are 0.0175 to 0.0254 and 0.0028 to 0.0178, respectively. The inclusion of flatter pipe slope data from the Cleveland sewerage system increased the overall range of average collection system variable, $\bar{S}$, by an order of magnitude. The average collection system pipe slope, $\bar{S}$, for the combined set of data assumed a more dominant role as an explanatory variable in describing the variance of estimated deposition solids loadings per collection system. A visual scanning of the average collection system pipe slope for the entire data set revealed a fairly reasonable spread of observations along the entire range, thereby minimizing the concern of spurious correlation created by data clustering at opposite ends of the range. The results for the simplest models (equations 4 and 8) shown in Table 2 are similar and confirm the above discussion in that the R^2 is 4.5% higher for the combined data set.

As a side note, the original models (equations 1 and 4) (derived from Eastern Massachusetts data) were used to estimate daily deposition loadings for the 28 Cleveland collection systems. The resulting R^2 values for the Cleveland data using the models generated from Eastern Massachusetts information are 0.717 and 0.811 for equations 1 and 4, respectively. The modified models (equations 2 and 8) (derived for the combined data set) were then used to estimate daily deposition loadings for the 75 Eastern Massachusetts collection systems. The R^2 values for the Eastern Massachusetts data using the models generated from the combined data base are 0.821 and 0.867 for equations 2 and 8, respectively. It is interesting to note in these numerical

sensitivity experiments that the degree of fits were superior in a predictive sense, for the simpler models (equations 4 and 8) in comparison to the elaborate approaches (equations 1 and 2).

The more favorable R^2 results for the simpler models (equations 4 and 8) suggests that the elaborate models (equations 1 and 2) are too specific and sensitive to charges in data input. In addition, the simplest of these procedures (equations 4 or 8) requires comparatively little input data compared to the more complex procedures. The user needs only to prepare estimates of the total collection system pipe length, L, the average collection system pipe slope, $\bar{S}$ and an estimate of the per capita waste rate, q, to use the simplest model.

Equations (4 or 8) are therefore preferred. Since the exponents of the independent variables and the multiplicative constant of the equation for equations 4 and 8 only slightly differ, equation 8, based on a broader data base, is recommended.

TABLE 3

COMPARISON OF DEPOSITION MODEL PREDICTIVE EQUATIONS

Equation	Data Source	R^2	Explanatory Variables
Elaborate (1)	E. Mass.	.949	L, S_{PD}, $S_{PD/4}$, q
Elaborate (2)	Combined	.940	L, S_{PD}, $S_{PD/4}$, $\bar{S}$, q
Simplest (4)	E. Mass.	.845	L, $\bar{S}$, q
Simplest (8)	Combined	.880	L, $\bar{S}$, q

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